# Spark Gap Switches for Radar

By F. S. GOUCHER, J. R. HAYNES, W. A. DEPP and E. J. RYDER

## Introduction

AN ESSENTIAL feature of radar is the generation, by means of an oscillator, of bigb-energy pulses of sbort duration, repeated many times a second. Tbe energy for these pulses is furnished to tbe oscillator from a power supply in a variety of ways. One of the most widely used of these is the "line type modulator" in which a pulse-forming network made up of a series of condensers and inductances is charged from the power supply through a choke and is then discharged hy a switch so that a suhstantially constant current will flow for a predetermined short time through the primary of a pulse transformer coupled to the oscillator. This switch is, therefore, an essential component of this type of modulator.

To meet the pulsing requirements of radar as it developed during the war, this line modulator switch was required to witbstand thousands of volts between pulses and to carry hundreds of amperes for the pulse duration which was of the order of microseconds. Also, the switching operation had to be repeated from a few hundred to a few thousand times a second for a total operating time of hundreds of hours. Furthermore, the dissipation of energy within the switch had to he very small in comparison with the energy delivered to the oscillator for efficient operation.

The switch which had the widest application in this type of modulator was that employing an electric spark. Of over 50,000 radars of various types manufactured by the Western Electric Co. during the war, over balf employed the electric spark in switching. One form of this switcb was a rotary spark gap, operating in air, in which the timing of breakdown was controlled mechanically. These gaps were successfully adapted to a variety of radar types including airhorne radar. However the demands for a more compact and lighter weight switch capahle of operating at lower voltages for airhorne radar led to the development of fixed sealed unit type gaps which, when connected in series, can be broken down electrically in a simple circuit.

Many problems had to be solved in the development of these switches. They required a considerahle amount of study, and with the aid of new techniques developed during the war, a number of significant measurements have been made which have extended our knowledge of sparks generally. It is the object of this paper to describe the results of some of these studies,

as well as to describe the essential characteristics of a variety of spark gap switches which were used in such numhers tbat they may he considered as an important contrihution to the war effort.

## I. Rotary Spark Gap Switches For Low Voltage Circuits

Rotary gaps were used successfully as switches in some of the earlier radar systems developed by Bell Telephone Laboratories. The switching voltages in the modulator circuits were relatively high, being in excess of 20 kilovolts. No trouhle was encountered in switching at the required pulsing rates nor in ohtaining satisfactorily long life. Fortunately the sparks tend to move about the electrode surfaces uniformly and the rate of erosion is such that with tungsten or molybdenum electrodes a uniformly small change in electrode dimensions is achieved which in no way interferes with satisfactory operation over long periods of time.

A difficulty was encountered, however, when the switching voltage was reduced to lower values, as required for applications in which the power supply voltages were limited. The gaps failed to hreak down regularly.

A particular application in which this difficulty was encountered was one in which the power supply was limited to 4 kilovolts, and in which 80 ampere pulses of one microsecond duration were required every 600 microseconds. The modulator circuit used was that shown schematically in Fig. 1 (a). The pulse-forming network includes the condenser elements which are charged through the choke and discharged hy the spark gap designed to hreak down at the required pulsing rate of 1600 per second. The load is the primary of a pulse transformer coupled to a magnetron and is closely equivalent to a 50-ohm resistance. The constants of the circuit are such that following the discharge of the network it is recharged sinusoidally along the solid line of Fig. 1 (h) to a peak value of approximately 8000 volts in $600 \times 10^{-6}$ seconds, at which point hreakdown must again occur and the operation he repeated. The dashed line is the approximate path of the charging voltage wave when hreakdown at the peak fails to occur.

A rotary spark gap was designed to meet these pulsing conditions. In this gap there are four fixed and four moving electrodes as indicated in Fig. 1 (a). These electrodes are tungsten rods 3 mm in diameter and ahout 15 mm in length mounted with their axes parallel and so spaced that the moving electrodes pass very close to the fixed electrodes with an overlap of ahout one-half their length. The speed of the moving electrodes is such that in the region of near approach the maximum gradients are those indicated in Fig. 1 (c). The solid curve shows the gradients when hreakdown takes place at the required time and the dashed curve the gradients when hreakdown fails to occur. Although the latter greatly exceed the normal

dielectric strength of air, sparking failed to take place a large fraction of the time.

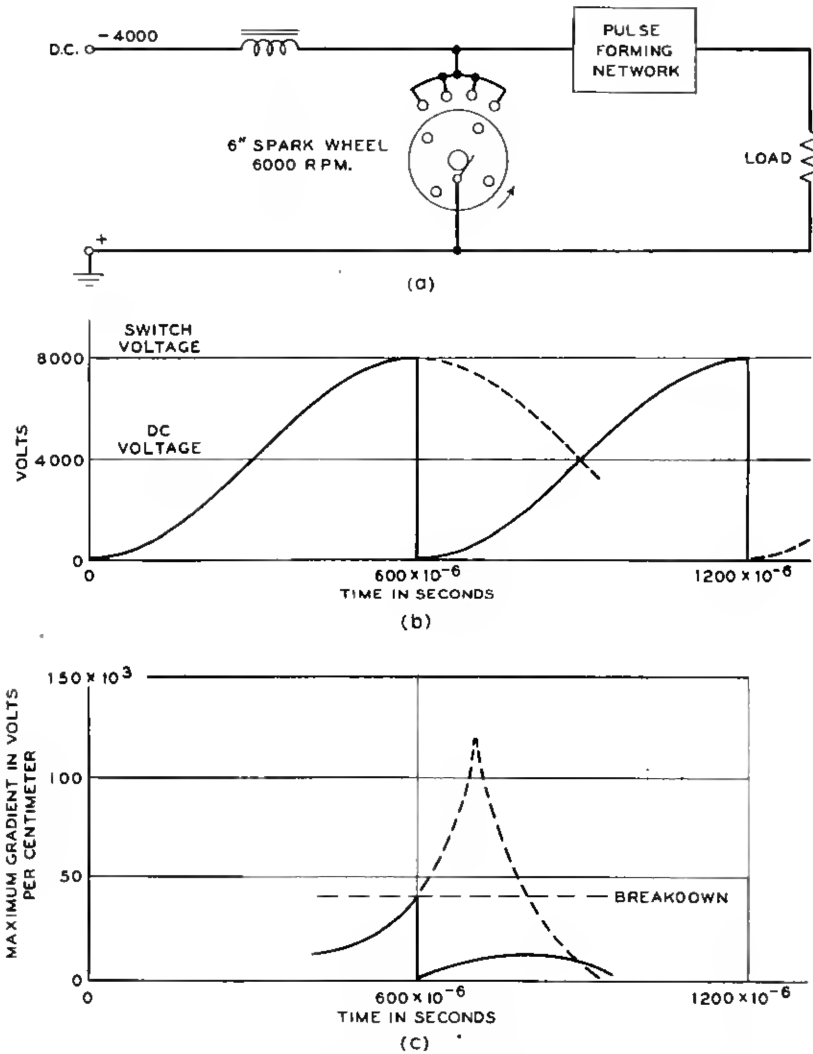


Fig. 1—(a) Line modulator circuit with rotary spark gap switch, (b) switch voltage vs. time, (c) maximum voltage gradient between electrodes vs. time.

Experiment indicated that this was caused by spark delay time, as irradiation of the cathodes by means of an ultra-violet lamp produced 100%

breakdown. This method of reducing spark delay time was not practical, however, and other means were sought. A solution was found through a rediscovery of the efficacy of corona prior to breakdown which came about through the introduction of a properly placed sharp edge on the cathode. Although this edge was apart from the sparking area of the cathode, 100% breakdown of the gaps was obtained and spark delay time so reduced

Fig. 2—Experimental model of rotary gap showing corona points.

that mechanical limitations alone controlled the variation in time of breakdown.

The essential features of the gap as finally developed for this project are shown in the photograph of an experimental model, Fig. 2, and in the perspective drawing and accompanying diagram, Fig. 3. The electrodes are of tungsten as in the earlier design, and corona points are introduced by the addition of the rods holding sharp metal points mounted on the same metal

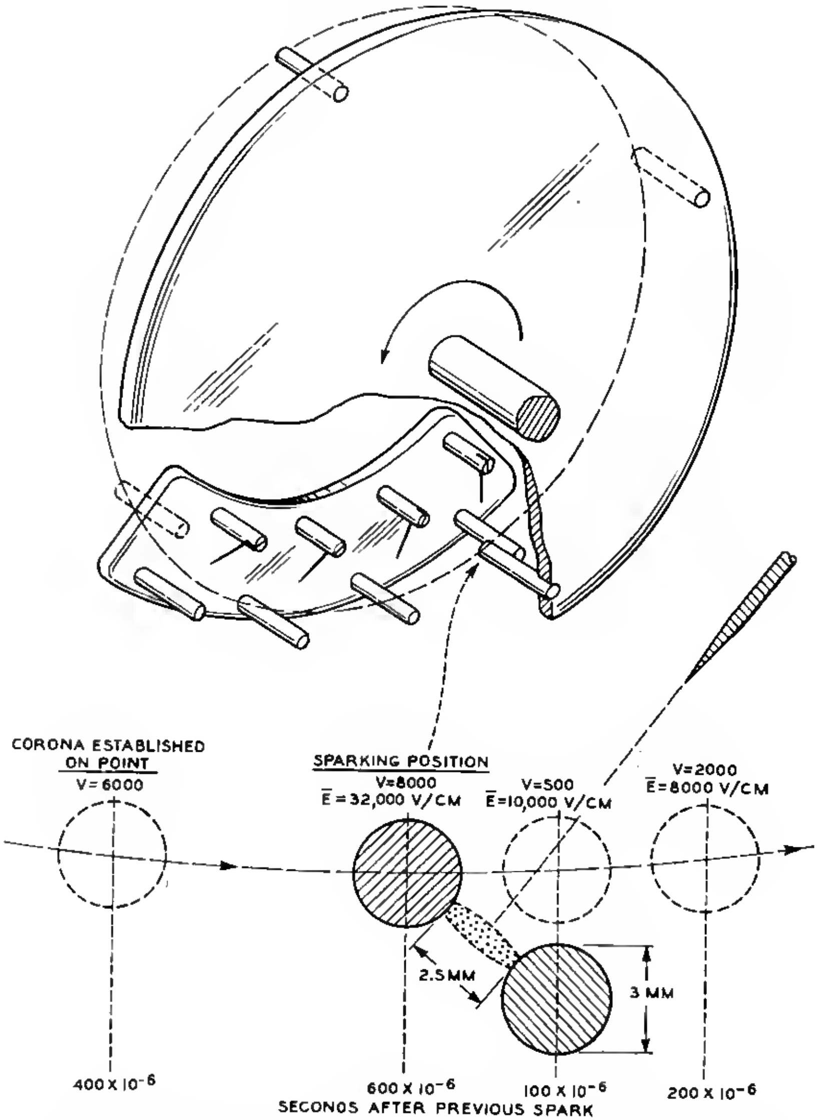


Fig. 3—Above, perspective drawing of rotary gap showing arrangement of corona points. Below, diagram showing voltage ($V$), and mean voltage gradient ($\bar{E}$) at various times in the spark-over region.

base as the fixed electrodes. The moving electrodes pass between the fixed electrodes and their associated corona points. This arrangement is clarified in the diagram which is a section through a plane normal to the electrode

axes and passing through the region of overlap. The shaded areas are for the sparking position as indicated and the location of the corona point is shown to scale. Experiment shows that when the moving electrode has reached the position corresponding to $400 \times 10^{-6}$ seconds after the previous spark, corona is established on the point. Thus the cathode is irradiated for $200 \times 10^{-6}$ seconds prior to breakdown.

No serious erosion problem was encountered when these gaps were operated for many hundreds of hours in air. No deterioration of the points was observed when their locations were properly adjusted so as to avoid sparking over to them. The cathode erosion rate is so low that appreciable flats were produced only after a hundred hours of operation. The anode erosion was estimated to be less than one-tenth of that of the cathode, and was doubtless associated with a small amount of reverse current shown to be present. The magnitude of the cathode erosion rate for tungsten in air is about twenty-five fold less than that for tungsten in hydrogen under the same conditions which indicates that oxygen plays an important and somewhat unexpected role in making practical the operation of these gaps.

There was, however, a serious corrosion problem when these gaps were adapted to airborne radar because of the necessity for sealing the modulator unit in a container capable of maintaining atmospheric pressure at high altitudes. Spark discharges in air are attended by the formation of both ozone and oxides of nitrogen, the latter combining with moisture to form nitrous and nitric acids. These reached such concentrations under continuous operation in the container that they were damaging to all enclosed equipment because of their corrosive action. A solution for this was arrived at after considerable study on the part of the Chemical Department. This consisted of the use of a copper impregnated activated carbon as an absorbent. With this absorbent a life of 500 hours was shown to be possible.

Over 10,000 rotary gap switches of this type were manufactured and used successfully in both ship and airborne radars. However, under the urge to reduce the weight of all possible components used in airborne radar and even to eliminate the necessity for pressurizing, the development of glass-enclosed fixed gaps as switches was diligently pursued.

The authors would like to acknowledge the cooperation of Mr. N. I. Hall of the Whippany Laboratories whose responsibility it was to engineer and develop these rotary gap switches for manufacture.

## II. Fixed Gaps

Preliminary experiment indicated that a series of fixed gaps could be made to operate satisfactorily as a modulator switch. A study was therefore made to determine the most suitable gas atmosphere, electrode material and gap design for use in sealed gaps. This led to the development of a unit

type gap, two or more of which could be operated in series. The first unit type gap had an aluminum cathode and a hydrogen-argon gas atmosphere. Later, under the urge for higher peak powers, mercury cathode gaps were developed. Details of this study and development will be discussed in this section.

(a) *Triggering Gaps in Series*

An alternative to a rotary gap in which the timing of spark breakdown is controlled mechanically was the use of a fixed gap, the breakdown of which is controlled electrically. One method of accomplishing this was to use a third electrode to which an impulse voltage was applied periodically at double the frequency of the resonant charging circuit. This voltage breaks down one gap with a discharge of energy furnished by the trigger circuit, which in turn causes a breakdown of the main gap, either through a modification of the field in this gap or through the addition of ions which reduce its breakdown voltage. This type of gap, however, required a strong air blast to de-ionize the gaps and, because of this, its use obviously presented no great improvement over the rotary gap. It was well known that the rate of de-ionization is greater the smaller the gap, so an attempt was made to trigger without air blast a number of smaller gaps which when connected in series would withstand the full switch voltage as employed in the rotary gap.

The arrangement used was that shown in Fig. 4. Six tungsten pins, 3 mm in diameter, were mounted with their axes parallel and spaced to give five 0.5 mm gaps. The switch voltage was divided by means of equal high resistances connected across the gaps, and a highly damped bi-directional trigger pulse was applied to the four middle pins through capacity coupling as shown. Corona points were also connected in such a way that the cathode of each of the gaps is irradiated in order to reduce the spark delay time.

By an appropriate adjustment of the circuit elements it was demonstrated that this series of gaps could be broken down by the trigger pulse and de-ionized with sufficient rapidity so that no air blast was required.

Although no attempt will be made here to elucidate the detailed steps in the triggering of the five gaps just described, we can get a qualitative idea of the process by considering a simple two-gap and three-gap circuit which, it turned out, was all that was required for the various applications of fixed gaps as they were eventually developed.

In the two-gap circuit, Fig. 5 (a), if the first half cycle of the trigger pulse and the switch voltage are both positive, gap 1 will break down when the potential at the mid point, due to the sum of the switch voltage and that of the trigger, is equal to the gap breakdown voltage, which for the moment we shall consider as singly valued. This effectively shorts gap 1 and throws the full switch voltage across gap 2 which in turn will break down provided this

switch voltage is equal to or greater than the breakdown voltage of one gap. The gaps will operate for all switch voltages up to a value equal to twice the breakdown voltage of one gap when both gaps will break down without the addition of trigger. This, then, is the maximum operating voltage and the ratio of maximum to minimum operating voltage is two to one on the basis of this simple picture.

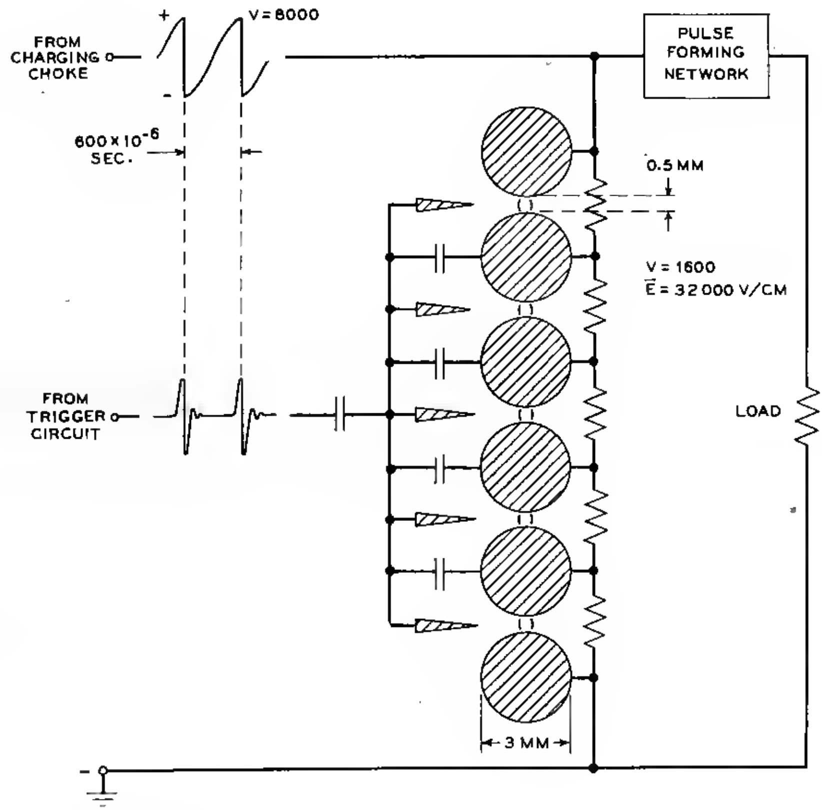


Fig. 4—Line modulator circuit with fixed gap switch composed of five 0.5 mm. air gaps triggered electrically.

In the case of the three-gap circuit, Fig. 5 (b), gaps 1 and 2 may be broken down by the simultaneous application of a trigger pulse through capacity coupling. The circuit elements can be so chosen that gap 1 first breaks down leaving enough trigger on gap 2, over and above that furnished by the switch voltage, to break it down. The full switch voltage is then applied across gap 3 and it will break down for values of switch voltage in excess of the

single gap breakdown voltage. In this case the switch voltage may be increased to a value three times that of the breakdown of one gap before the three gaps can break down without addition of trigger. Thus the ratio of maximum to minimum operating voltage is three to one. Ideally this ratio may be increased by the addition of more gaps.

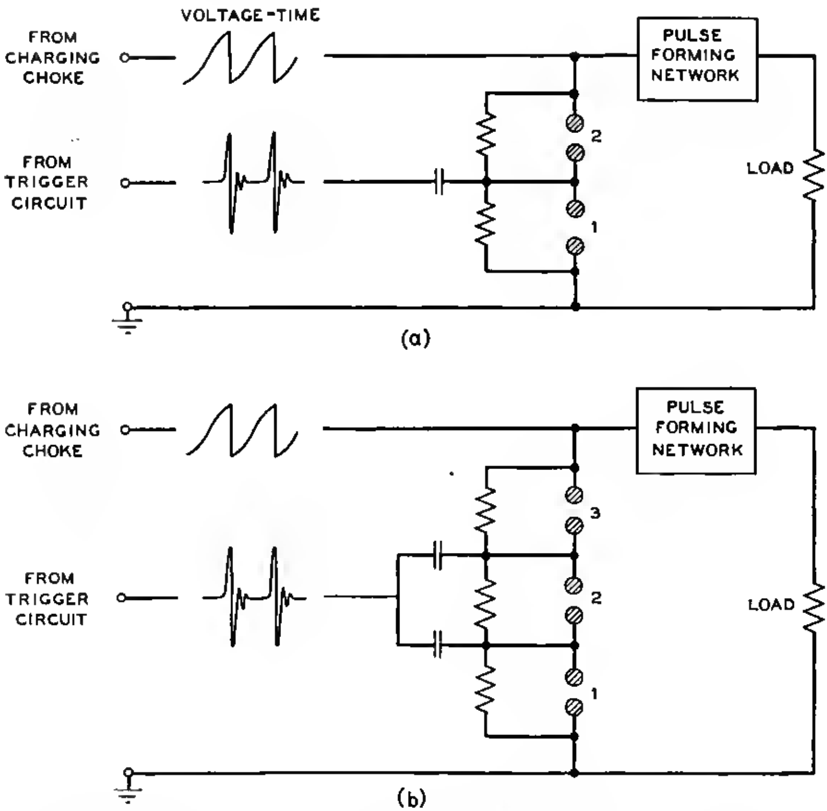


Fig. 5—Line modulator circuit (a) using two fixed gaps as switch, (b) using three fixed gaps as switch.

The operating characteristics of actual gaps do not conform exactly to this simple picture as we shall see later. This is because the breakdown voltage of a gap is not singly valued but depends on a variety of conditions such as rate of rise of applied voltage, pulsing rate, and the energy of the pulse, as well as the type of gap employed. However, we may regard it as a qualitatively correct picture of the operating characteristics of series gaps.

A more complete description of operating characteristics will be given in a

later section, but, in view of the fact that the gap itself plays an important part in these characteristics, it seems desirable to describe first the gap types with which we have to deal.

(b) *The Hydrogen-Argon Aluminum Cathode Gap*

Following the successful triggering of fixed gaps in air witbout the use of air blast for their de-ionization, experiments were undertaken with sealed gaps in various gas atmospheres using simple rod electrodes having their axes parallel. A large number of gases were tested and the conclusion reached that hydrogen was the most satisfactory because of its bigh de-ionization rate. With it fewer and wider gaps were required to meet a given pulsing condition. Three 4 mm. gaps in hydrogen at pressures somewhat less than atmospheric were approximately equivalent to the five 0.5 mm. gaps in air already referred to. Thus, from this point of view, the use of hydrogen would very greatly simplify the prohlem of making practical gaps.

The spark in hydrogen, particularly with relatively small peak currents, was, however, unsatisfactory in that it terminated in a high-pressure glow with a high cathode drop rather than the low drop required for efficient switching. The addition of about 25% argon corrected this and about this proportion was used successfully in the gaps with which we are concerned in this report.

Although the required operating conditions were met with this gas mixture, cathode erosion or sputtering was so excessive with all readily available cathode materials that this factor appeared as the chief obstacle in the way of making practical gaps. The sputtered material was deposited on all surfaces in the form of a fine powder which eventually destroyed the insulation, therehy limiting the useful life of the gaps to a few hours.[1]

A promising lead was, however, obtained in the case of aluminum cathodes. It was observed that some of the sputtered material deposited on the anodes opposite the cathodes from which it was removed. This deposit was reasonably compact and smooth, which suggested the possibility of reducing by gap design the extent of harmful scattering. This might be achieved by increasing the amount of sputtered cathode material which is deposited on the anode or returned to the cathode within the sparking area.

The tube, Fig. 6, was an early attempt in this direction. This tube had three 4 mm. gaps hetween flat electrodes, the cathode surfaces having raised portions to confine the sparking witbin their areas. The gaps were

[1] At about this time we learned that the British had developed sealed gaps triggered by means of an auxiliary electrode and known as "Trigatrons." These were high pressure gaps containing argon with a small amount of oxygen to reduce sputtering of the electrodes. The life of these gaps was determined by the time required to clean up this oxygen. Though these were tried it was decided to follow an independent development avoiding if possible all clean up effects.

operated successfully for somewhat over 100 hours before enough scattered material accumulated to interfere with gap insulation. A uniform spark distribution was maintained throughout this time and measurement showed that aluminum was removed quite uniformly from the raised portion of the cathode to a depth of only a fraction of a millimeter. An equally thick

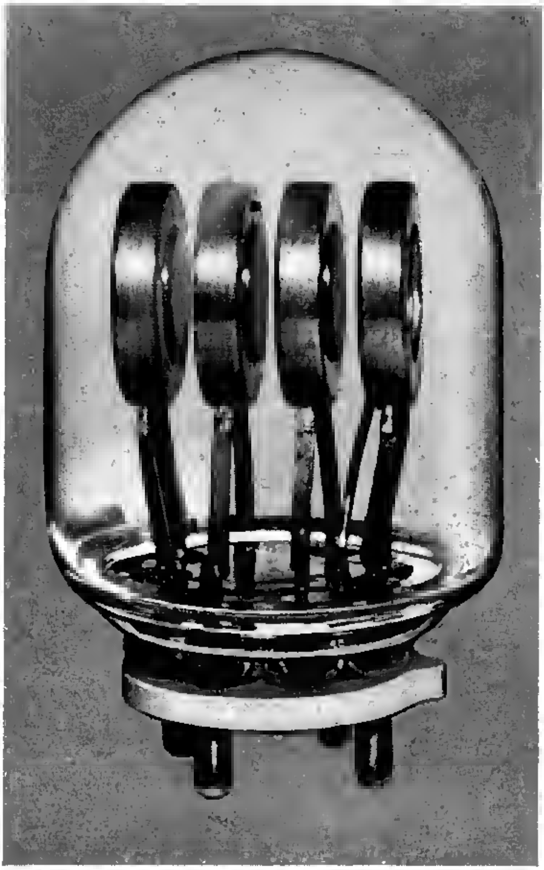

Fig. 6—Three gap tube having aluminum electrodes and a hydrogen-argon atmosphere—actual size.

though somewhat rougher deposit was formed on the opposing anode surface, thereby retaining the gap spacing very satisfactorily. About 30 milligrams of loose material were scattered throughout the tube.

A more drastic but also more successful design change was introduced by making three separately enclosed gaps, one of which is shown in the photo-

graph and radiograph, Fig. 7. In these gaps the sparking area of the cathode was hemispherical in shape, partly surrounding a spherical anode. These gaps were operating successfully at the end of 1000 hours. The scattered material was deposited on only a portion of the glass envelope of

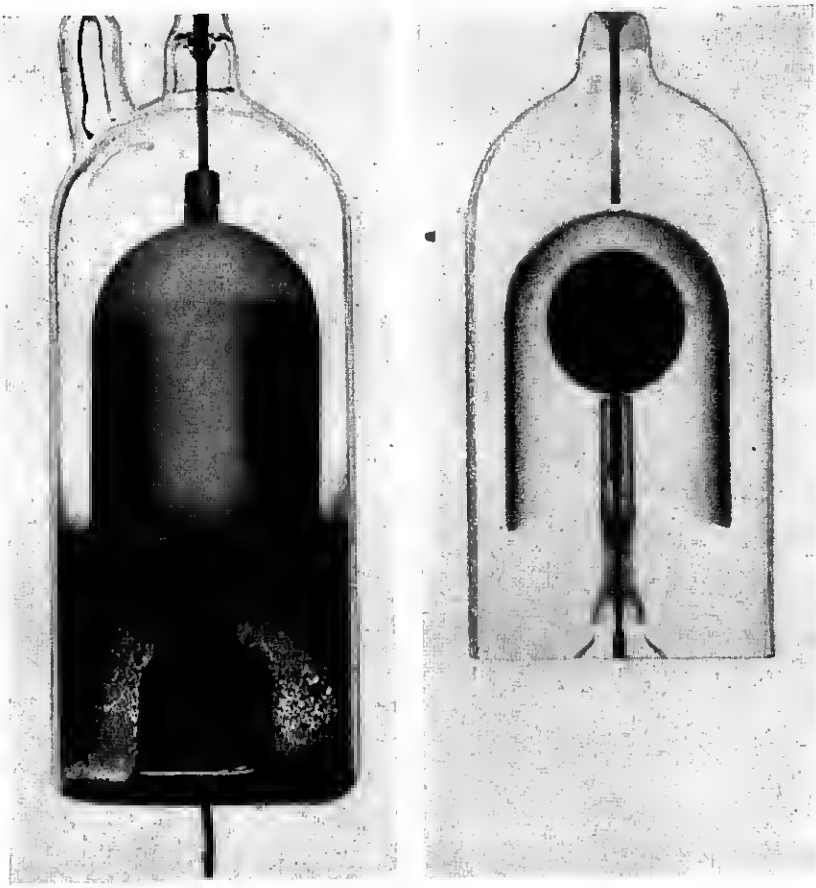

Fig. 7—Photograph and radiograph—actual size—of the first unit type gap having a re-entrant aluminum cathode, a spherical aluminum anode and a hydrogen-argon gas atmosphere, after operating 1000 hours with a 40 ampere pulse of one microsecond duration repeated 1660 times a second.

each gap, as shown in the photograph. The extent of the material removed from the cathode and deposited on the anode, as shown in the radiograph, was such as to cause no marked change in gap spacing. Furthermore, the operating range remained substantially constant throughout the 1000 hours of operation as shown in Fig. 8. This was an important observation since it

indicated that there is no gas clean-up effect associated with gap operation, a fact that was later proved by careful measurement of gas pressure before and after operating gaps of this type. A section through the anode of this gap, Fig. 9 (a), shows that the anode deposit is not compact but assumes the form of a coral-like structure. This low-density deposit must, however, be electrically equivalent to a compact surface as shown by the constancy of the operating characteristics with time.

In view of the success of this design it was decided to develop gaps of the unit type having anodes well enclosed by the cathode surfaces. An attempt to make a more practical gap is that shown in the photograph and radio-

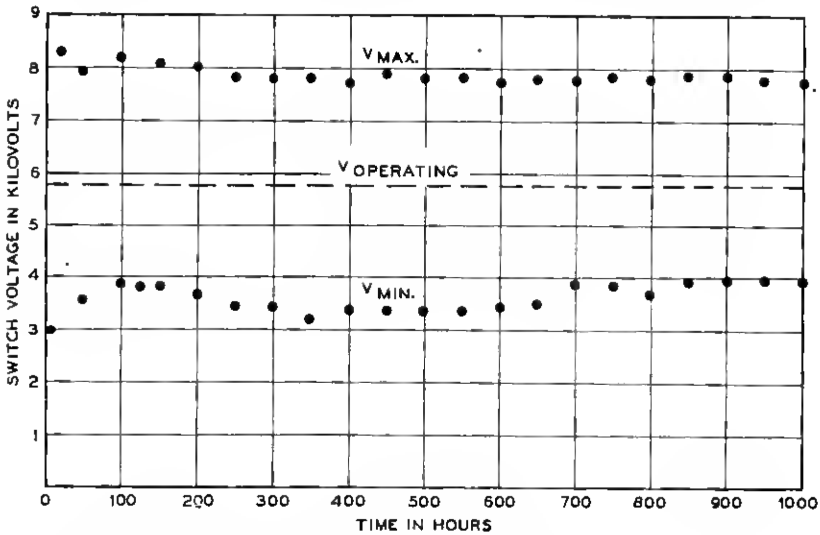


Fig. 8—Maximum and minimum operating voltages as a function of time, for three unit gaps of the type shown in Fig. 7, when operated in series.

graph, Fig. 10, both of which were taken after 750 hours operating time. In this gap the anode is an aluminum rod rounded at the end mounted concentrically with tbe enclosing catbode which has a hemispherical closed end. The corona point was added to facilitate starting. Because of the higher anode gradient the sparking was confined to the end region of the tube as indicated in the radiograph, and for this reason we have designated this design an "end sparking tube". A section through the anode, Fig. 9 (h), shows a deposit which in this case is compact due to the fact that the moving spark is confined to a smaller area than in the previous tube, Fig. 7 (a). It is to be noted also that the scattered material is less in extent than that

obtained with the first design, pointing to a more effective trapping of the sputtered material.

Weight loss measurements made under a variety of pulsing conditions show that though the rate of cathode erosion is somewhat dependent on the

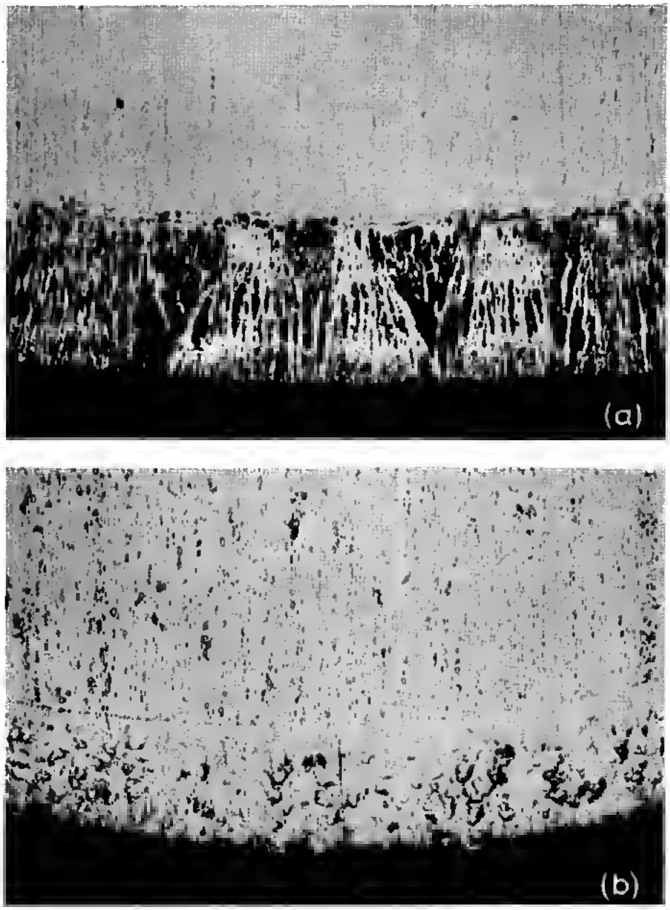


Fig. 9—Photomicrographs (×50) of sections showing anode deposits for (a) unit gap shown in Fig. 7, (b) unit gap shown in Fig. 10.

pulse duration, it depends to a much greater extent on gap design. Erosion rate measurements in terms of grams per coulomb are shown in Fig. 11 for the two gap designs there indicated and for pulse durations varying from one to five microseconds. It is clear that the open gap type of design in which the cathode is small leads to a loss which is at least five fold greater than

that of the "end sparking" type of gap. The smaller loss in the case of the latter shows that much more material returns to the cathode for resputtering

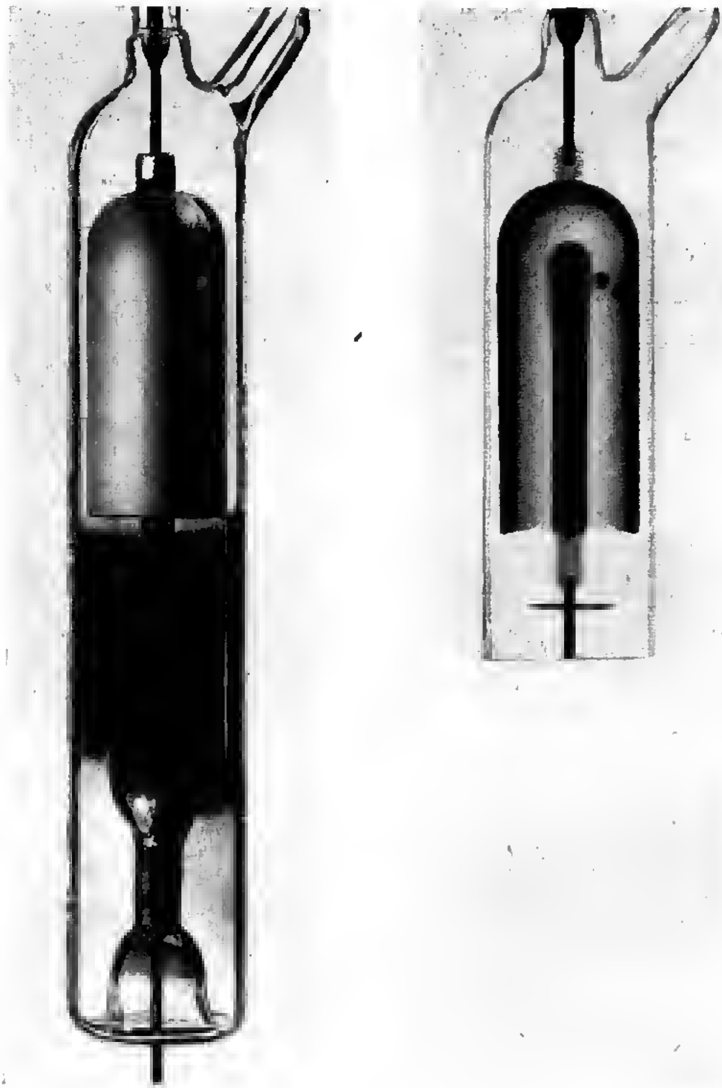

Fig. 10—Photograph and radiograph—actual size—of end sparking unit gap, after operating 700 hours with a 65-ampere pulse of one microsecond duration and repeated 1660 times a second.

than in the case of the former and supports the use of the unit type gap in which this process can be utilized. A cylindrical cathode enclosing a rod

anode also behaves in this way and its erosion rate differs but little from the "end sparking" type of tube; in fact, the practical gaps to be described in II-(f) are essentially of this type.

With these facts in mind it would appear that gaps could be designed to meet a variety of pulsing conditions if the total number of ampere hours for a pre-assigned life were known, for the electrode areas could be so adjusted that the changes in gap spacing would be as small as required. Analysis of the gradients associated with the end sparking type of gap shows that there

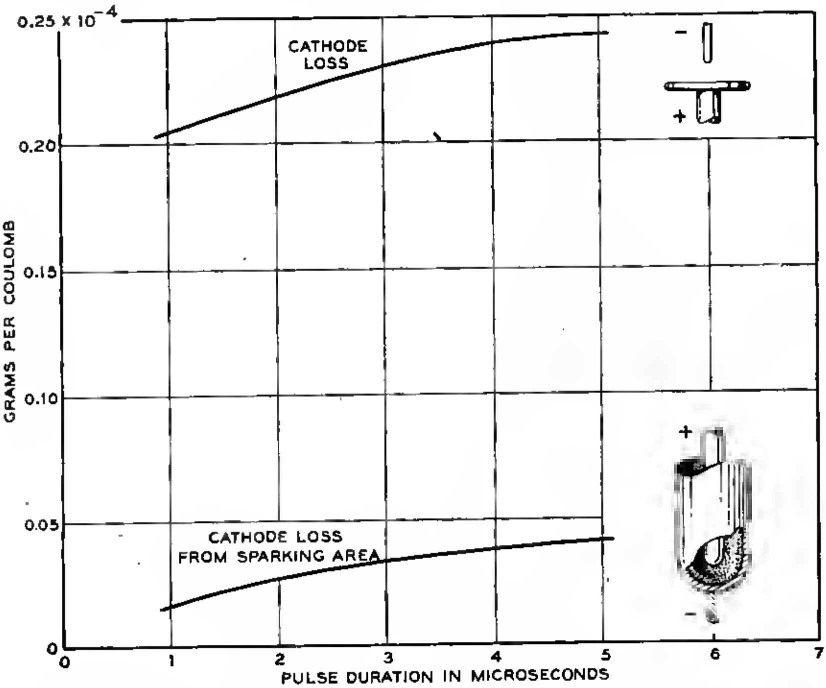


Fig. 11—Cathode loss, in grams per coulomb, as a function of pulse duration showing effect of gap design.

can be a considerable build-up on the anode before there is much change in the maximum gradient which determines the spark-over voltage.

Experience with gaps designed for a variety of pulsing conditions showed that substantial anode build-ups could be tolerated without interfering with operating conditions, but not as much as theory would predict for an unexpected factor had a controlling influence on gap life. This factor was the failure of the spark to keep moving under certain conditions with the result that spikes were grown on the anode which introduced a rapid deterioration

of the operating range due to an increase in anode gradient and also in part to a decrease in gap spacing.

Both the relatively large anode build-up, which may be tolerated without interference with gap operation, and the nature of spike growth, which limited useful life, are illustrated in the radiographs, Fig. 12. It is to be noted that the spike is almost of uniform cross section along its length and radiographs made at various stages of its formation show that growth takes place

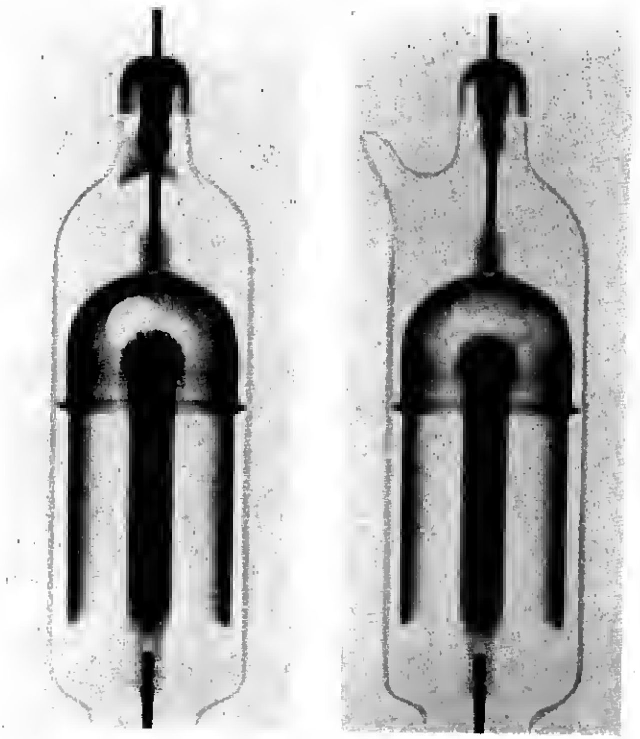

Fig. 12—Radiographs showing two views of the uniform deposit and subsequent spike growth on the anode of an end sparking unit gap.

at its end. This indicates a high concentration of negative ions in the vapor prior to deposit on the anode.

Life test data in which the pulse repetition rate was kept constant at 200 per second are shown in Fig. 13 for gaps having a fixed spacing but in which the peak current is varied (a), and for gaps having a variety of spacings but in which the peak current is kept constant (b). The life is measured in terms of hours to the beginning of spike growth. Both "end sparking" and "side sparking" tubes were employed in the tests. These data clearly show that

if lives longer than 500 are to be obtained, there is a limiting peak current of about 70 amperes with gap spacings of 250 mils or with a peak current of 70 amperes there is a minimum spacing of 250 mils. Similar data were obtained indicating a different critical spacing for other pulsing conditions.

This factor of a critical gap spacing imposed an important restriction on gap design for it was desirable to make gap spacing as small as possible for any given project. This follows because of gap size and weight, also—as we shall see in II-(e)—because of switching efficiency. This led to the development of a variety of unit gaps as described in II-(f).

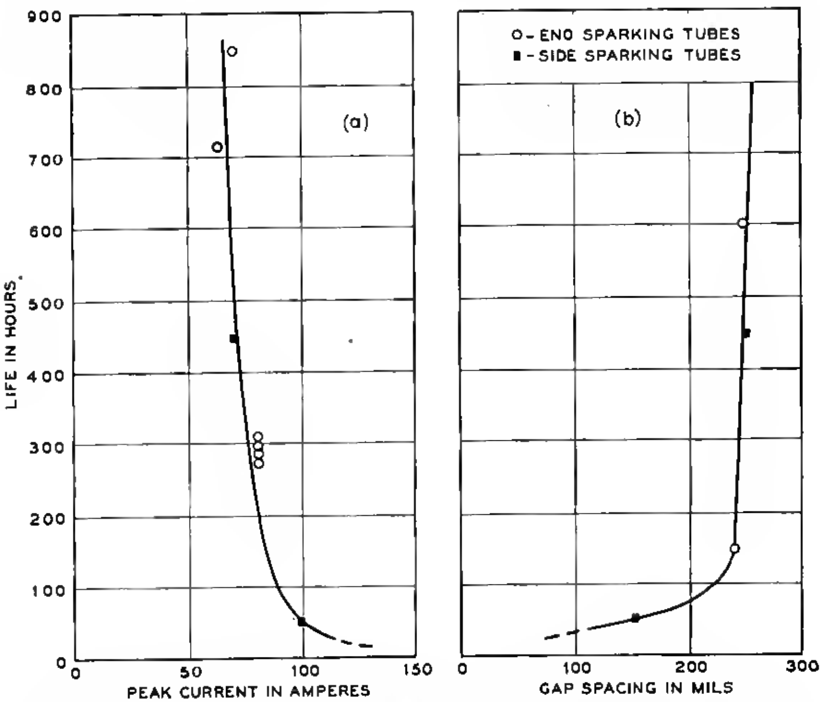


Fig. 13—Life in hours measured to the beginning of spike growth obtained with 5-microsecond pulses repeated 200 times a second (a) for a 60-mil gap and various peak currents, (b) for a fixed peak current of 70 amperes and various gap spacings.

## (c) *The Mercury Cathode Gap*

Early in the study of the aluminum cathode gap it was realized that the sputtering difficulty might be largely if not entirely eliminated through the use of mercury as a cathode and the suppression of reverse current to avoid sputtering of the anode. It was shown that simple mercury pool cathode

gaps could switch peak powers in the megawatt range for long periods of time with stable operating characteristics. Under the urge for still higher powers than those which were handled by the aluminum cathode gaps, experiments were undertaken to develop a mercury cathode type of gap.

The main difficulty in the way of using mercury as a cathode is a mechanical one, as the conditions of operation of spark gap switches, particularly for

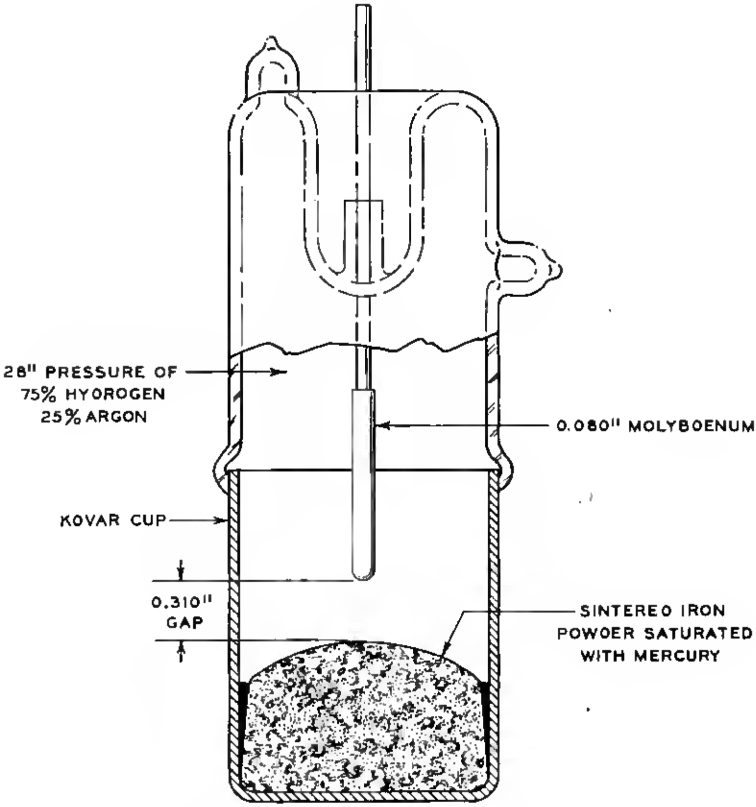


Fig. 14—Schematic drawing of an iron sponge mercury cathode unit gap—actual size.

airborne radar, demand that the sparking surface be rendered substantially quiescent. Preliminary experiments were made with metal baffles as damping agents and with metal wicks to furnish a mercury sparking surface. The latter led to the development of a sintered iron sponge saturated with mercury as the best means of obtaining a satisfactory cathode.

The constructional details of one of the earliest tubes of this type are given in the sketch, Fig. 14. The sintered iron sponge, a cross section of which is

shown in the photomicrograph Fig. 15, is about 60% porous. It was prepared by pressing iron powder in the Kovar cup and sintering in a hydrogen atmosphere. A special heat treatment to remove oxide made it possible to fill all pores of the sponge with mercury and to supply a mercury film on its surface. Under sparking conditions mercury from this film is evaporated and is condensed on the tube walls, eventually returning to the cathode. Due to capillary action the film is continuously replenished. This film protects the iron sponge from sputtering provided that there is sufficient

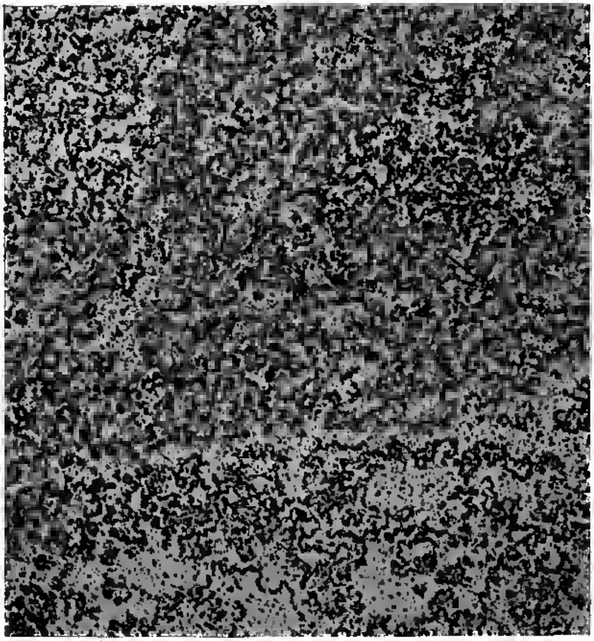

Fig. 15—Photomicrograph (×15) of a section through a sintered iron sponge showing porosity.

cooling of the cathode to maintain the mercury film at a temperature below its boiling point.

These gaps are not temperature sensitive as are most electronic devices containing mercury. This is because the mercury vapor plays no essential role in the spark discharge, as indicated by the fact that dissipation measurements—discussed in II-(e)—show its dependence on the hydrogen-argon rather than on the nature of the cathode material. With adequate cathode cooling gaps of this type operate satisfactorily over a range of ambient temperature at least from −50°C to over 100°C. Practical gaps constructed

with iron-sponge mercury cathodes were developed to the manufacturing stage, as discussed in II-(f).

In addition to being capable of switching higher peak powers than aluminum cathode gaps, the mercury cathode gaps can be designed to have superior operating characteristics. Through the use of small radius anodes not possible with the aluminum cathode gaps, a wider operating range and much less time "jitter" can be attained. The small anodes build up corona at voltages less than those of breakdown, thus furnishing radiation prior to breakdown. For special applications, gaps have been developed having a range approaching 3 to 1 in a two-gap circuit, capable of switching 10 megawatts peak power, for many hundreds of hours, and having a time "jitter" of less than 0.02 microseconds at the operating voltage.[2, 3]

### (d) *Starting and Operating Characteristics*

It has already been stated in II-(a) that starting and operating characteristics of series gaps cannot be interpreted simply because, under the circuit conditions of rapidly varying voltage, the breakdown voltage of a spark gap is not singly valued. Because of spark formation time the minimum voltage at which a spark gap will break down increases as the rate of rise of the voltage across it increases. Further, due to spark delay time, the voltage across the gap at breakdown is usually still higher than this minimum value. It is therefore impossible to designate a unique breakdown voltage of a spark gap when the voltage across it is increasing with time. It is, however, possible to find a practical minimum and maximum breakdown voltage for a particular rate of rise of voltage. The difference between this maximum and minimum value is a measure of the maximum spark delay time. It is for the purpose of reducing this spark delay time that corona points (or radium) are introduced, and it will be shown that the value of both spark delay time and spark formation time have an important bearing on the operational characteristics of fixed gaps.

In addition to rate of voltage rise, the breakdown voltage of a spark gap depends on the amount of ionization in the gap due to a previous spark. When a spark discharge stops, a column of highly ionized gas is left in the gap. Although this column is rapidly de-ionized by recombination and diffusion of ions, a lower breakdown voltage is found for many microseconds in consequence of this residual ionization. The minimum value of the breakdown voltage of the gap is therefore a function of the time

[2] F. S. Goucher, J. R. Haynes and E. J. Ryder, High Power Series Gaps Having Sintered Iron Sponge-Mercury Cathode, P.B. 19640, U. S. Department of Commerce, Office of the Publication Board.

[3] J. R. Dillinger, Operation of Sintered Iron Sponge-Mercury Cathode Type Series Gaps at S.C.I., A.E.W. and 5 Microsecond Conditions, P.B. 13270, U. S. Department of Commerce, Office of the Publication Board.

after the spark ceases and is called the re-ignition voltage of the gap. It will be shown that this re-ignition voltage determines to a large extent the starting voltage of tbe fixed gaps.

Before describing the sequence of events required for starting and operating, it is desirable to define our terms more precisely than we have defined them up to this point. The minimum operating voltage is the lowest switch voltage at which the tubes will continue to break down 100% of the time under the action of the trigger pulse, and the maximum operating voltage is that higher switch voltage at which spontaneous hreakdown of the series of gaps never occurs. Thus the operating range of voltage is that which includes those voltages existing across the series of gaps, at the time of application of trigger pulse, for which the tubes always break down under the action of the trigger pulse but never hefore. Starting voltage is defined as the minimum value of d-c voltage at which a series of gaps can be made to hreak down under the action of the trigger pulse. Starting thus differs fundamentally from operating in that while operating demands that the series of gaps always breaks down under the application of the trigger pulse, starting requires only that the gaps break down once in many trigger pulses occurring in a fraction of a minute. Thus, a starting voltage is always lower than the minimum operating voltage. However, due to the doubling of the switch voltage when starting occurs, the d-c power supply voltage required to start may be higher than the d-c power supply voltage at the minimum.

The results of a quantitative oscillographic analysis of starting and operating characteristics of a pair of preproduction W. E. 1B22 tubes[4] are now presented in detail, for they are qualitatively representative of all spark gaps. These tubes operate in a two-gap circuit, a schematic of which is shown in Fig. 5 (a). The analysis is carried out by an examination of the voltage-time wave which occurs at the point of application of the trigger pulse, the midpoint of the two gaps. It will help in understanding the oscillograms[5] which follow if it is borne in mind that the voltage across gap 1 is the voltage shown on the oscillogram with respect to ground or "O" voltage, while the voltage across gap 2 is the voltage shown on the oscillogram with respect to the switch voltage.

The sequence required for starting is shown in Fig. 16 (a). Just before the application of the trigger pulse the voltage at the midpoint of the two gaps is half that of the applied d-c hy virtue of the resistance divider. When the trigger pulse is applied, the voltage rises to $A$ (3.8 kv) which is the minimum breakdown voltage for these tubes with voltage rates of rise encountered in the trigger pulse. Gap 1, therefore, may break down at $A$

[4] These tubes contain both corona points and radium to reduce spark delay time (see II-(e)).

[5] The time scales of these oscillograms are expanded in regions of very rapidly reversing voltage in order to make clear the sequence of events.

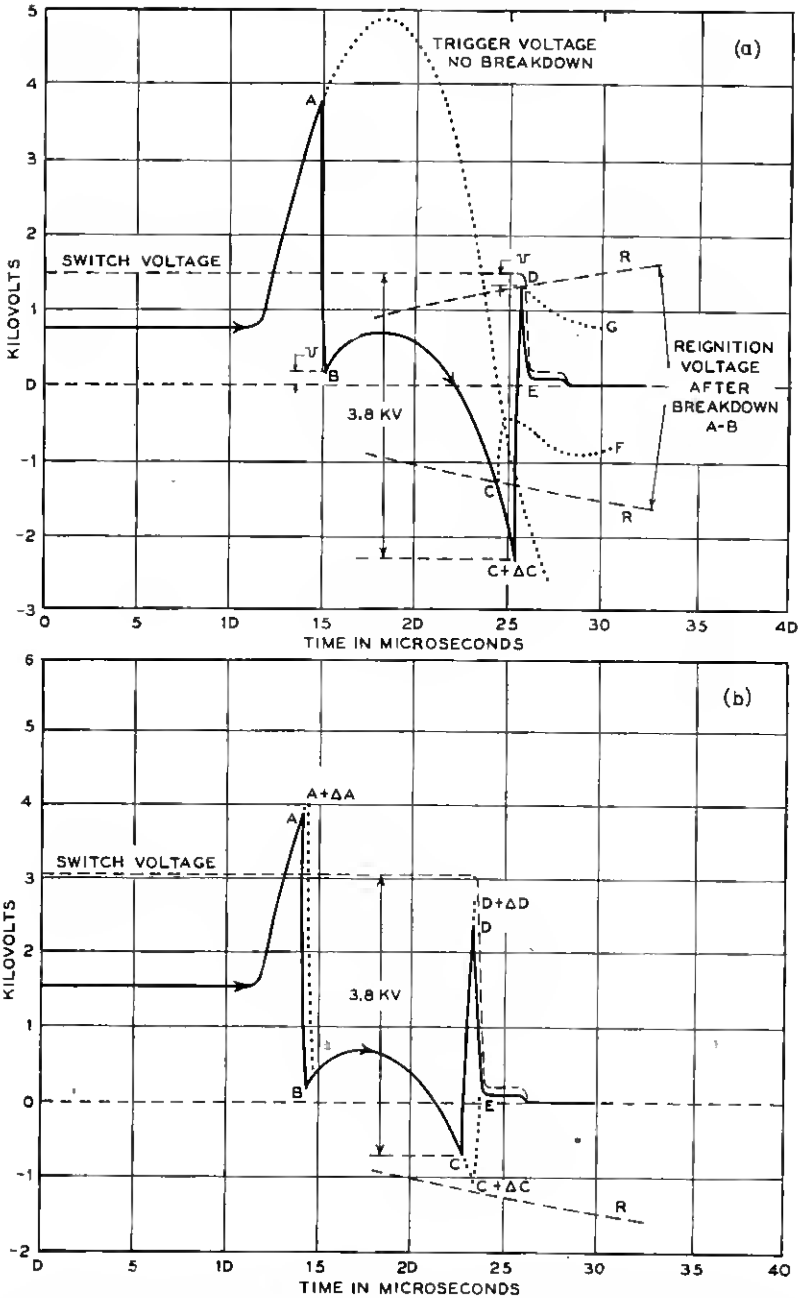


Fig. 16—Oscillographic traces of voltage vs. time as measured at the mid-point of a two-gap circuit during breakdown of 1B22 tubes, (a) for starting, (b) for operation at minimum switch voltage.

passing a low-energy spark supplied hy the trigger circuit. In consequence of this, the voltage drops sharply to $B$ and then the discharge stops since the voltage ($v$) remaining is insufficient to maintain the discharge. This voltage, called the extinguishing voltage, is ahout 0.2 kv for these low energy sparks. Gap 1 is now ionized and has the independently measured re-ignition voltage characteristics, $R$, as shown. Under the action of the trigger pulse the voltage then proceeds to $C + \Delta C$ when gap 2 may break down since it has the minimum required voltage across it (3.8 kv). When this occurs, the voltage rises sharply to $D$, which falls short of the switch voltage hy the amount of the extinguishing voltage ($v$). At this point gap 1 may re-ignite. If this occurs both gaps are simultaneously conducting and the switch voltage drops to $L$ while passing the high-current pulse of energy from the network. This sequence occurs relatively infrequently.

Because of spark delay time, instead of hreaking down at $A$, gap 1 may hreak down at some higher voltage, or not at all. Instead of gap 2 hreaking down at $C + \Delta C$, gap 1 may hreak down in the reverse direction at any voltage higher than $C$, its re-ignition voltage, and is only prevented from doing so hy spark delay time. Also, hecause of this delay time, gap 1 will usually fail to re-ignite at $D$, its re-ignition voltage, and since $D$ is also the extinguishing voltage ($v$) for gap 2, the potential will drop to $G$ under control of the trigger pulse. If any one of these things occurs the gaps will not start on that particular application of trigger pulse. However, since the pulses are applied at the rate of many hundred a second, it is usually only a fraction of a second until the desired sequence is obtained.

From the conditions essential for the consummation of each of the three steps necessary for starting, it follows that the starting switch voltage $V_{dc}$ must he equal to $A - (R + \Delta C)$ or $v + R$, whichever is the greater. Since $R$, the re-ignition voltage, increases with time, $A - (R + \Delta C)$ decreases while $v + R$ increases with time. A minimum for $V_{dc}$ will, therefore, be ohtained when the period of the trigger voltage wave is such that when gap 2 hreaks down,

$$A - (R + \Delta C) = v + R, \tag{1}$$

and since also for this minimum

$$V_{dc} = A - (R + \Delta C) \tag{2}$$

we get

$$V_{dc} = \frac{A - \Delta C + v}{2}. \tag{3}$$

By suhstituting the ohserved constant values of $A$, $\Delta C$ and $v$ in (3) we get $V_{dc} = 1.5$ kv, which is the value of switch voltage depicted in the diagram. This diagram is, therefore, that for optimum period of the trigger voltage

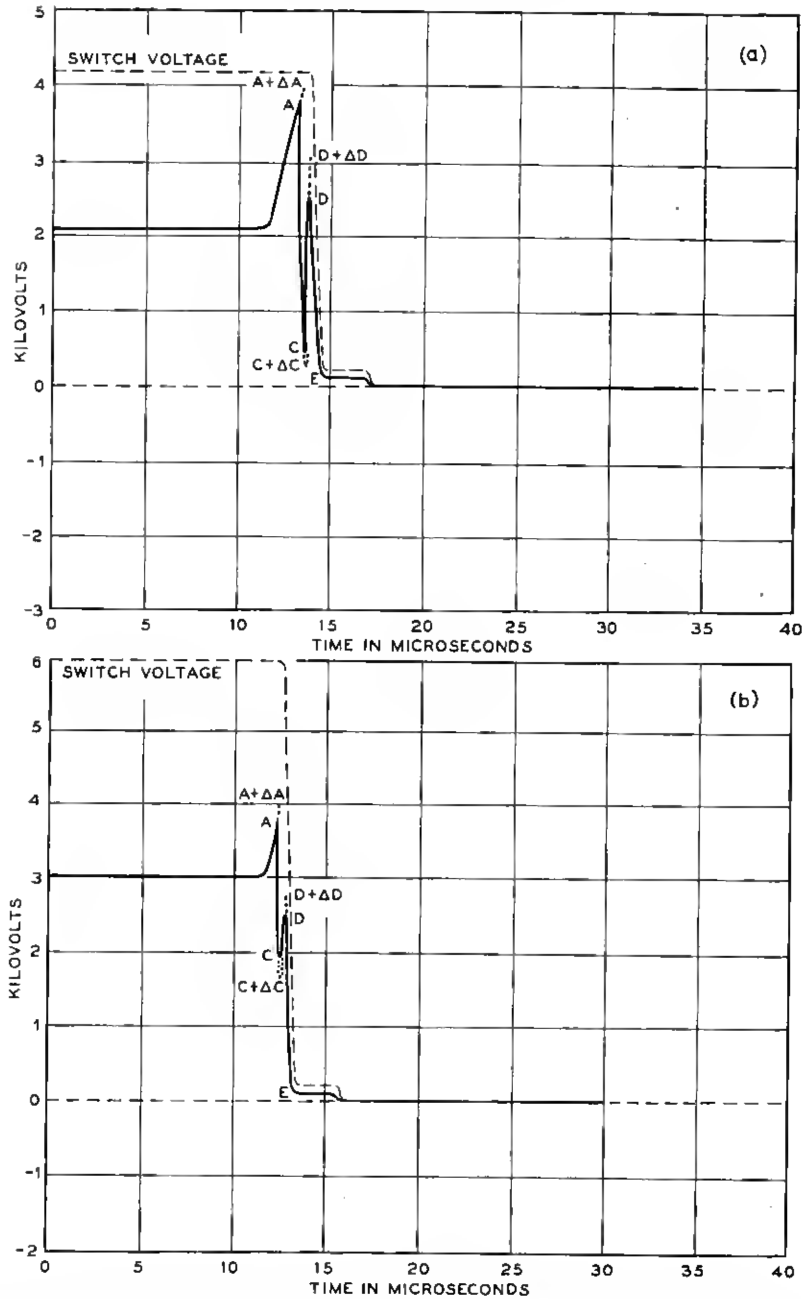


Fig. 17—Oscillographic traces of voltage vs. time as measured at the mid-point of a two-gap circuit during breakdown of 1B22 tubes (a) for normal operating switch voltage (b) for operation at maximum switch voltage.

wave. That this is actually a minimum was demonstrated experimentally by varying the period of the trigger pulse. $V_{dc}$ increased for pulse periods both greater than and less than that shown in the diagram. The increase was small and so is of no great practical interest, but it does confirm the prediction made on the basis of the above analysis.

After the tubes have started the switch voltage is nearly double the d-c voltage, and the tubes will operate continuously if the switch voltage is above the minimum operating voltage. The sequence of events near the minimum operating voltage is shown in Fig. 16 (b). During operation the spark delay time is much less than during starting, as indicated by a smaller voltage is established.

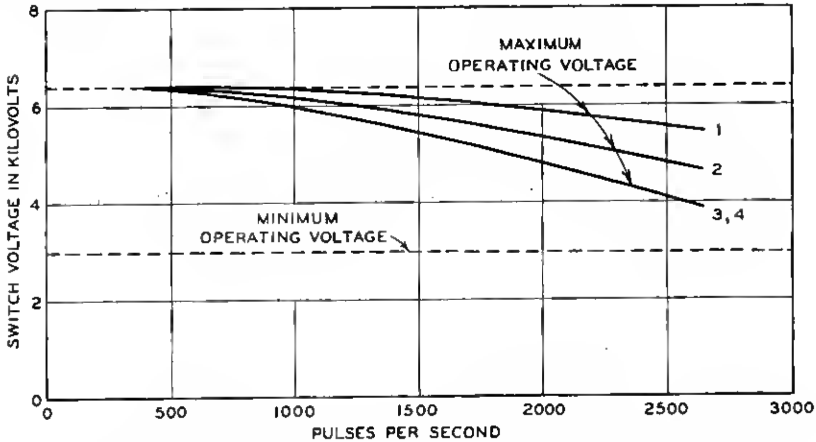


Fig. 18—Maximum operating voltage of 1B22 tubes in a two-gap circuit as affected by pulse repetition rate for a variety of pulsing conditions as follows:

| Curve | Pulse Duration in Microseconds | Load in Ohms |
|---|---|---|
| 1 | 0.75 | 55 |
| 2 | 0.75 | 30 |
| 3 | 0.75 | 15 |
| 4 | 1.50 | 30 |

Of course, no spark gap tubes are designed to operate very close to their minimum operating voltage. A margin of safety is always maintained. The characteristics of these tubes with a switch voltage at a practical operating voltage is shown in Fig. 17 (a). Gap 1 breaks down between $A$ and $A + \Delta A$ and before gap 1 is extinguished gap 2 breaks down between $C$ and $C + \Delta C$. Since in this case both gaps are conducting simultaneously, the main pulse passes without re-ignition of gap 1. The voltage at the midpoint of the two discharges rises to a value between $D$ and $D + \Delta D$, due to the rapid change of spark impedance. This sequence always takes place since ample margin is provided.

## CORRECTION FOR ISSUE OF OCTOBER, 1946

In the article *SPARK GAP SWITCHES FOR RADAR*, lines 2–14 inclusive on page 593 should have appeared between lines 10 and 11 on page 588.

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If the switch voltage has been increased to a value near the maximum operating voltage, the voltage-time characteristic shown in Fig. 17 (b) results. Exactly the same sequence occurs as before. However, if the voltage be slightly increased above the value shown, the gaps can break down spontaneously during the network charging cycle and before the application of the trigger pulse, even though the value of $A$ is some 20% greater than the charging voltage applied to the gap. This is the expected effect of spark formation time on minimum breakdown voltage since the rate of rise of trigger voltage is far higher than that of the network charging voltage. When spontaneous breakdown occurs, because of circuit conditions, both the rate of rise of the voltage of the network charging cycle and its peak value are increased. Since the switch voltage arrives at a higher value in a shorter time, spontaneous breakdown is most likely to occur again. The effect is cumulative so that, after a few increasingly frequent cycles, an arc is established. It is clear that this arcing must never be allowed to occur in the operating range.

These characteristics were taken while using a current pulse of 0.75 $\mu$s duration at a repetition rate of 1000 per second and a 30 ohm resistance load. This produced a peak current at the maximum operating voltage closely closely equal to the switch voltage divided by twice the resistance load, or about 100 amperes. Under these conditions, due to the relatively low pulse repetition rate, there is little residual ionization in the gaps at the time of the next pulse, so that the gaps have closely recovered their maximum breakdown voltage. However, as the pulse rate is increased, thus decreasing the time between pulses, the value of switch voltage at which the gaps break down spontaneously is found to decrease due to residual ionization. Thus the maximum operating voltage is a function of the pulse repetition rate.

The decrease of the maximum operating voltage as a function of pulse rate, for these tubes, is shown in Fig. 18 for a variety of pulsing conditions.

Curve 2 was obtained with the 0.75 $\mu$s pulse and a 30-ohm load. It will be observed that the maximum operating voltage decreases with pulse rate in the expected manner.

If the peak current of the pulse be decreased, fewer ions are produced in the spark and so at any given time after the pulse one would expect less residual ionization in the gaps. Curve 1 was obtained by keeping the pulse duration the same as before but increasing the load resistance to 55 ohms. Thus the current at a given switch voltage was reduced to 30/55 of its former value. It will be seen that, as predicted, the drop of maximum operating voltage with increased pulse repetition rate is less.

Conversely, if the current is increased the opposite effect is produced. Curve 3 was obtained by decreasing the load resistance to 15 ohms while keeping the pulse duration constant. This gives twice the peak current at

the same switch voltage as that of Curve 2 with a resultant increased residual ionization and a decrease of maximum operating voltage at the higher pulse repetition rates.

If, instead of doubling the current, the pulse duration be doubled, a similar increase in residual ionization is produced. Curve 4 was obtained by doubling the pulse duration (1.5 $\mu$s) and using a 30 ohm load. Thus, while the current is the same as Curve 2, the current pulse has twice the duration. It will be observed that for these pulses, doubling the time of pulse is the equivalent of doubling the current.

One might expect that the minimum operating voltage would also decrease as the pulse repetition rate is increased. However, experimentally it is found that, for these tubes, the minimum operating voltage is nearly constant and, therefore, independent of residual ionization. This result is produced largely because the maximum breakdown voltage of the gaps at the extremely high rate of voltage-time change encountered in triggering at the minimum is little affected by this amount of residual ionization.

Since the minimum is nearly constant the operating range of voltage of these tubes is a decreasing function of the pulse repetition rate, current, and pulse duration. This is in general true of all fixed spark gaps; however, the amount of decrease of operating range depends on the spark gap spacing, gas atmosphere and geometry of the electrodes.

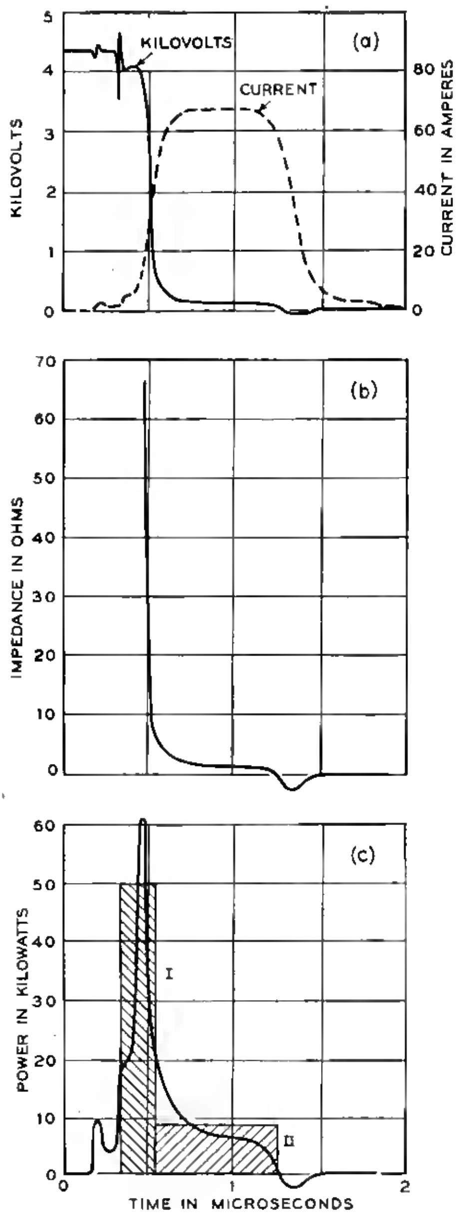
(e) *Dissipation and Switching Efficiency*

In II-(d) we considered the voltage-time relationships leading to the simultaneous breakdown of series gaps. In this subsection we will consider the voltage and current relationships with time during this breakdown, and their bearing on spark dissipation and switching efficiency.

In Fig. 19 (a) are shown a voltage-time and current-time trace obtained oscillographically with a pair of 1B22 gaps. The voltage is measured across both gaps and corresponds to the dotted traces shown for switch voltage in Fig. 17 (a). The current pulse is shown in proper time relationship with the voltage trace. Similar traces are obtained for any pulse duration and peak current. These, then, may be considered as typical of all pulses produced by spark switching with these gaps.

In Fig. 19 (b) is plotted the impedance of both gaps with time, from which we see that the impedance of this switch falls rapidly in a small fraction of a microsecond to an average value of only a few ohms while the main current pulse is passing. The tail of the trace showing a negative impedance is due not to the gaps but to inductance inherent in their leads.

The solid trace, Fig. 19 (c), shows the product of voltage and current in kilowatts plotted against time. The integrated area of this plot corresponds to the dissipation per pulse of both gaps. This area is independent of the




(a) Voltages vs. time and current vs. time for 0.75-microsecond pulse.

(b) Impedance vs. time.

(c) Instantaneous power dissipated in gaps vs. time—solid trace from oscillographic, shaded areas from calorimetric measurements.

Fig. 19—Pulse characteristics of two 1B22 tubes operated in series.

pulse repetition rate, enabling one to determine the gap dissipation for any project by multiplying the loss per pulse by the repetition rate.

This area can be divided into two parts as suggested by the two sbaded blocks I and II. The first part corresponds to the energy dissipated initially hy the trigger and then by the pulse forming network in the brief transient period when the voltage across and the current through the gaps are changing rapidly. The former is comparatively small and usually can be neglected. The latter attains a maximum value of power when the impedance of the gaps approximates that of the load. The second so-called steady state part, corresponding to block II, represents the energy lost during the main pulse

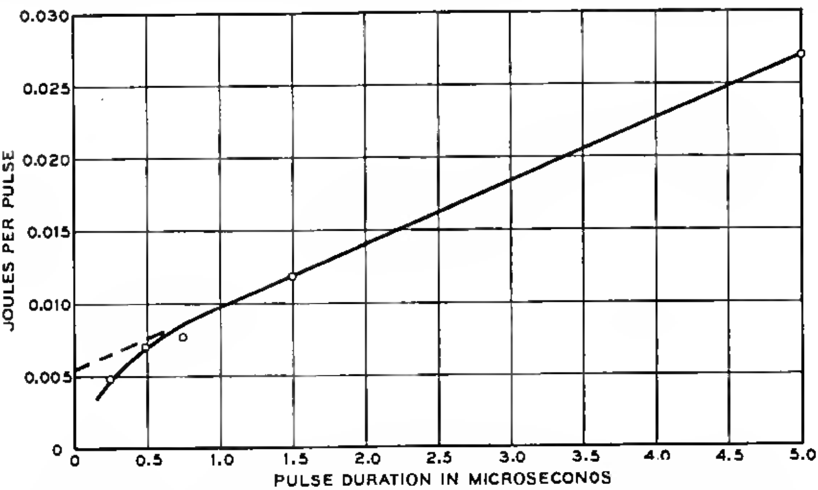



Fig. 20—Dissipation per gap per pulse vs. pulse duration for 1B22 gaps operated in series with a peak current of 70 amperes.

when the impedance of the gaps is low and comparatively constant. Its value will depend on both the pulsing conditions and the gaps themselves.

A calorimetric study was made of the dissipation of gaps as affected by various parameters. This method was superior to the oscillographic approach in that it afforded greater accuracy and ease of measurement. The curve, Fig. 20, shows observations in terms of joules per pulse per gap obtained calorimetrically with the 1B22 type tube as a function of pulse duration in microseconds. The peak current in all cases was 70 amperes and the trigger energy was included. It is clear that for pulse durations greater tban 0.5 microseconds the dissipation $D$ in joules per pulse per gap is given by

$$D = A + Bt \tag{1}$$

where $A$ is the intercept of the extrapolated solid straight line through the value of $\Delta A$ and $\Delta C$. There are reasons for believing that this is due primarily to the higher electrode temperature, but is doubtless aided by residual ionization left over by the high-energy sparks now passing. As a consequence the first gap always breaks down at voltages intermediate between $A$ and $A + \Delta A$. Gap 2 always breaks down at voltages between $C$ and $C + \Delta C$, below the re-ignition voltage of gap 1, and gap 1 always re-ignites at voltages between $D$ and $D + \Delta D$ allowing the main pulse of current to current to pass at a voltage $E$. However, if the switch voltage is decreased, $C + \Delta C$ will occasionally cross the re-ignition voltage characteristic $R$ of gap 1. Gap 1 can then re-ignite and thus the gaps will not fire on the application of that trigger pulse. A second way in which the gaps can miss is by failure of gap 1 to re-ignite at $D$. Even though either of one of these events occurs only once in many thousands of pulses, a minimum operating observed points and where $B$ is the slope of this line. The shaded blocks I and II of Fig. 19 (c) were obtained from values of the two terms $A$ and $Bt$, respectively, showing graphically the agreement between the calorimetric and the oscillographic methods.

As a result of calorimetric measurements on a wide variety of gaps having either aluminum or mercury cathodes and operated under a wide variety of pulsing conditions, we have been able to establish an empirical formula for the dissipation $D$ in joules per pulse per gap in terms of these gap parameters and pulsing conditions as follows:

$$D = 5.7(10)^{-7} I_p S + [40 + 3.9(10)^{-2} p^{0.4} S] I_p t. \qquad (2)$$

Here $I_p$ is the peak current in amperes, $S$ the gap spacing in mils, $p$ the gas pressure of hydrogen-argon in inches of mercury, and $t$ is the duration in seconds of an idealized square-top wave equivalent in ampere-seconds to the actual current wave. This formula holds for either aluminum or mercury cathodes and is independent of gap design. It is modified only slightly when pure hydrogen is substituted for the hydrogen-argon mixture, the constant $3.9(10)^{-2}$ becoming $3.1(10)^{-2}$. It is based on many measurements in which the parameters covered the following ranges:

| Parameter | Range |
|---|---|
| $S$ | 40–350 mils |
| $p$ | 28–50″ Hg. |
| $t$ | $1\text{–}6 \times 10^{-6}$ seconds |
| $I_p$ | 45–1070 amperes |

After calculating the value of $D$ from Equation (2) the dissipation in watts per gap for any project is obtained by multiplying by the pulse repetition rate. This equation does not include the trigger energy dissipated which usually

can be neglected but which can be measured independently and added if so desired.

It is to be noted that the first or transient term of the formula is unaffected by pulse duration and argon content and depends at least to a first approximation on only the peak current and length of spark. The numerical constant includes the time of this transient, the average gradient during this period, and a factor to reduce the peak current to an average value. The portion of the second or steady state term within the brackets represents the average voltage across a gap when it is highly conducting and is approaching the characteristics of a steady arc. This average voltage is separated into two parts. The first part, 40 volts, is the sum of the cathode and anode drops arising from space charges at the electrodes. The second part is the voltage drop along the positive column which has a pressure dependent uniform gradient and which is of the order of 100 volts per cm. It is only this gradient which is perceptibly altered when argon is added to the hydrogen.

From this formula it is possible to calculate the switching efficiency for any design of gap and set of pulsing conditions within the specified range of parameters covered by the formula. Calculation shows that with three gaps in series the switching efficiency in all projects was at least 90%, whereas with two gaps in series it was in most cases as high as 96%.

(f) *Development of Fixed Gaps for Manufacture*

The designs of the fixed gaps for manufacture were dictated by the requirements of particular modulators. Under the code numher of each of the gaps a brief description is given of the electrical and mechanical requirements which had to be met.

*W.E. 1B22*

The 1B22 fixed gap tube is an aluminum cathode type with a hydrogen-argon filling. An exterior and a cross-sectional view are shown in Fig. 21. This fixed gap tube was developed for the modulator of an airborne radar known initially as ASH and later an AN/APS-4. In this modulator two tubes are used in series to switch a peak power of about 105 kilowatts into a W.E. 725A magnetron. It was desirahle that the peak voltage in the modulator section be kept fairly low so that the circuit would perform satisfactorily at high altitude even when the pressurizing container was damaged. Furthermore, the equipment was to be very compact and light in weight.

In order to meet the requirements of this radar, two tubes were used in series with a peak switching voltage of 4 kilovolts. They were required to pass a current pulse of 67 amperes for 0.75 microseconds at two repetition

rates, one of 600, the other of 1000 pulses per second. They were also to operate for short periods at 2.25 microseconds and 330 pulses per second. The main problems in the design of such a tube were those of obtaining an adequate service life and a sufficiently low starting voltage.

As pointed out in II-(b), the life of an aluminum cathode gap of this type is critically dependent upon the anode-cathode spacing. For this tube a

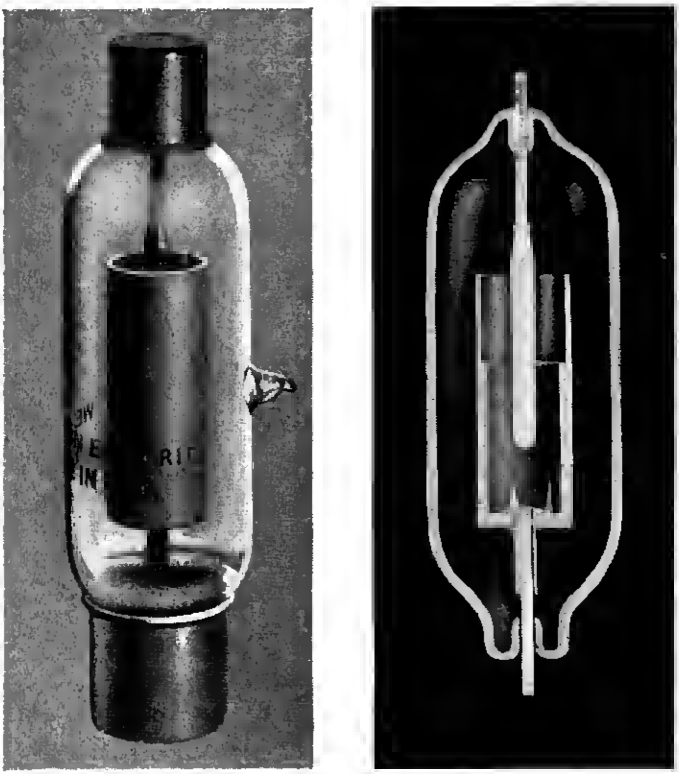


Fig. 21—Western Electric 1B22 spark gap tube.

spacing of approximately 150 mils was selected, the gas pressure being 20 inches of 75% hydrogen and 25% argon. This gave a life of about 500 hours for the 0.75 microsecond pulse, and a much shorter life for the 2.25 microsecond pulse. However, since the latter pulse duration is used only a small part of the time, the service life proved to be adequate. In order to obtain the maximum life from each tube, it was necessary that the anode and the cathode depart no more than a few mils from concentricity. Otherwise the sparking would not be uniformly distributed radially, leading to a

non-uniform anode build-up and a shortened life. Furthermore, in order to prevent failure of the tube, due to sputtered material destroying the insulation of the interior glass walls, the inside diameter of the cathode was enlarged near the open end, thus confining the sparking to the deeper portion of the catbode cylinder.

As discussed in II-(d) the starting voltage of a pair of fixed gap tubes is particularly important. The operating voltage of the tubes in this case is approximately 4 kilovolts which is derived from the resonant charging of the pulse shaping network condensers from a high voltage supply of about 2.2 kilovolts. The open circuit voltage of this supply is about 2.7 kilovolts. This, then, is the voltage available for starting the gaps. In order to make the gaps start at a voltage well below this value, corona points were introduced at the end of the cathode opposite the end of the anode, a small quantity of radium was also introduced in this region, and the anode diameter was reduced to the lowest value consistent with long life. The effectiveness of the corona points and the radium was reduced by the sputtered material during the life of tbe tube, but the irregular deposition of this sputtered material favored the production of corona and actually reduced the starting voltage to a lower value than that for a new tube.

The tube was designed for fuse clip mounting but it was found that the acceleration imparted to the tube when it was snapped into heavy clips was greater than that encountered in flying service. Accordingly, a special mounting was devised so that the tube would not be broken when being installed in the radar set. By the end of the war these tubes had been installed in approximately 15,000 radar equipments.

*W.E. 1B29*

The 1B29 fixed gap tube is similar in constructional details to the 1B22 except that it is smaller, the gap spacing being only 90 mils. An exterior and a cross-sectional view of the tube are shown in Fig. 22.

The gaps were designed to switch 2.8 kilovolts and to pass a peak current of about 27 amperes for 0.75 microseconds at a repetition rate of 2000 pulses per second. The main design problems were tbose of adequate life and stability of tube drop during conduction.

The small size of these gaps resulted in a life of only 300 hours which was, however, quite adequate for this application. As pointed out in II-(b) the argon was added to the hydrogen to ensure a uniform low impedance on sparking. The extremely small peak current required an increase in the amount of argon to 50% instead of the usual 25%.

In mechanical construction, the 1B29 is essentially a scaled-down 1B22. Because of the smaller size of the tube, no new problems existed in making it rugged.

Sufficient tubes were manufactured to supply approximately 3000 radar equipments.

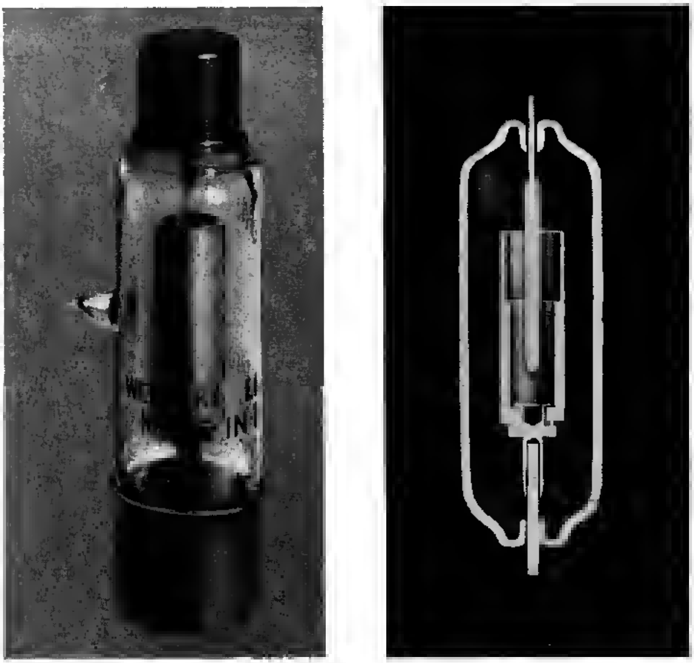


Fig. 22—Western Electric 1B29 spark gap tube.

### *W.E. 1B31*

The 1B31 fixed gap was also an aluminum cathode gap, with a gap spacing of 300 mils and 24 inches of 75% hydrogen and 25% argon. An exterior and a cross-sectional view are shown in Figure 23. This gap was developed for an airborne radar. This modulator was required to furnish a peak power of 230 kilowatts to a W.E. 2J53 magnetron. The modulator was also to provide a range of pulse durations and repetition rates extending from 0.25 microseconds at 1600 pulses per second to 5.0 microseconds at 200 pulses per second.

In order to meet these requirements, two 1B31 tubes were used with a peak switch voltage of 8 kilovolts and a peak current of 75 amperes. By using a 300 mil spacing, a life greater than 500 hours was obtained at 200 pulses per second, 5 microseconds and 75 amperes. The other operating conditions were less severe from the life standpoint.

The wide spacing used meant a considerable increase in the size of the cath-

ode over the previous designs. To make this tube rugged, both electrodes were supported from large diameter kovar-to-glass seals. During assembly the cathode end of the tube was open so that a tool could be inserted to hold the anode concentric with respect to the cathode, while its supporting member was sealed to the glass. A cup was then brazed in to cover the cathode opening.

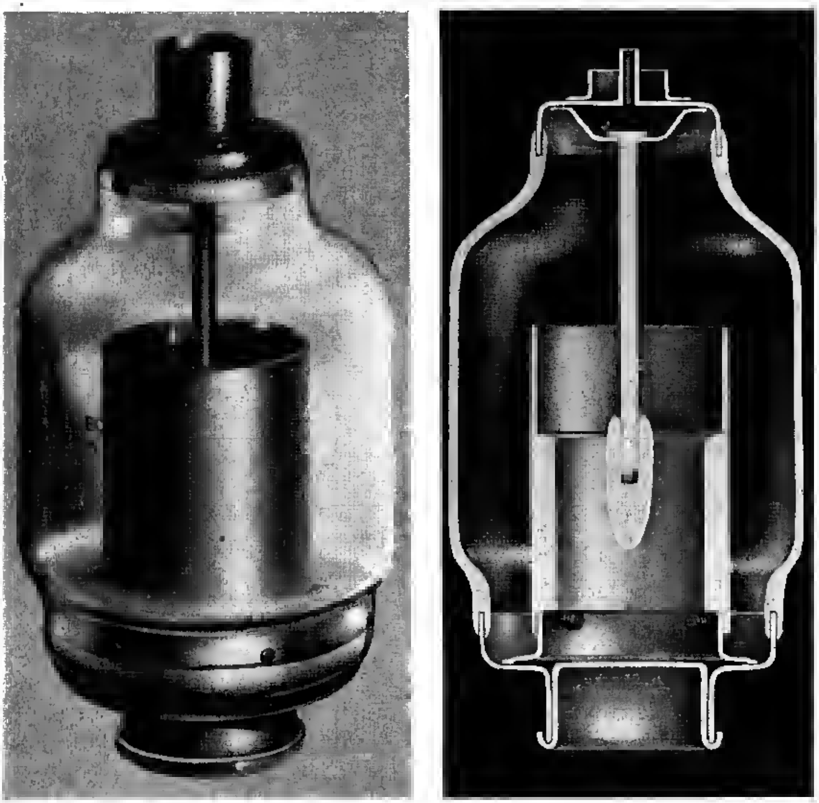


Fig. 23—Western Electric 1B31 spark gap tube.

Several hundred models of this tube were made in the laboratory and performed satisfactorily in the circuit. Due to circuit design changes, however, these tubes did not go into large scale manufacture.

### *W.E. 1B42*

The 1B42 fixed gap tube departs considerably in design from the 1B22 and 1B29 in that mercury instead of aluminum was used as cathode. Its

construction is illustrated in Fig. 24. This tube was developed for radars which were for long range search on shipboard. In these modulators three tubes were used in series to switch a peak power of 0.8 megawatts and 1.4

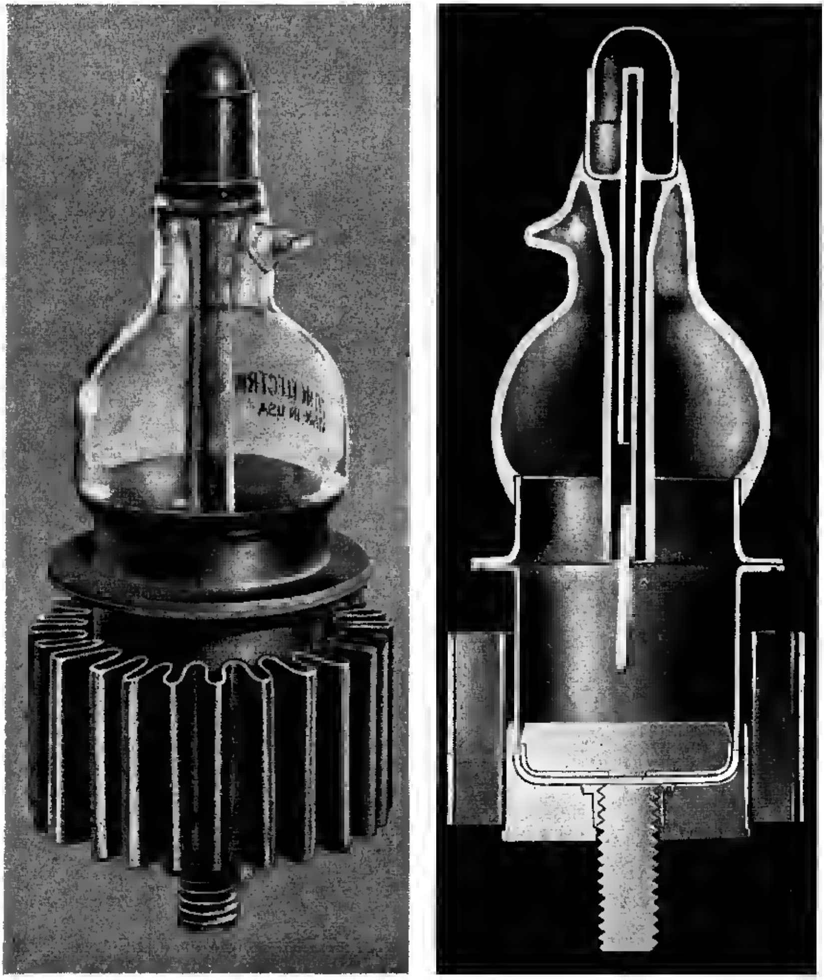


Fig. 24—Western Electric 1B42 spark gap tube.

megawatts, respectively, into high power triode oscillators. These modulators were to be capable of operation at either half or full power. The equipment was to be capable of withstanding the shock and vibration normally encountered on shipboard.

The series of gaps was required to operate with peak switch voltages

varying from 10.5 to 17.1 kilovolts, and to pass a maximum current of 200 amperes for 6 microseconds at a repetition rate of 180 pulses per second. They were also required to operate with 1.5 microsecond pulses at 600 pulses per second. The main electrical design prohlems were those of ohtaining a wide voltage operating range and an adequate life with large peak currents and long pulses.

As discussed in II-(c), the use of an iron sponge mercury cathode with a molyhdenum rod anode provided a wide voltage operating range as well as a long life with 200 ampere, 6 microsecond pulses. The mercury sponge cathode also met the vihration and shock requirements of shiphoard operation.

In order to secure good wetting of the sintered sponge, which was essential to a long life, a special construction, as shown in Fig. 24, was used. The sponge was sintered directly into the hottom of a Kovar cup which had six radial vanes welded into it. These served to anchor the sintered material as well as to conduct the heat away from the center of the cathode. After the anode assemhly and glass envelope were attached to the upper Kovar flange, the two suh-assemhlies were welded together hy means of a single ring weld. This allowed a minimum of handling of the sintered material and eliminated all glass work after the sintered material was inside the tuhe.

The processing of the tuhe consisted of first evacuating and then of heating the lower portion to 800°C while passing purified hydrogen through the tuhe. After the sponge had partially cooled, the mercury was introduced and wetting took place instantly.

Since the temperature of the center of the sponge must he kept helow the hoiling point of mercury, in addition to the internal vanes descrihed, the Kovar cup was soldered into a hlock of copper to which was attached a folded copper radiator.

Several hundred models of the tuhe were made in the lahoratory and delivered to the Navy and to equipment manufacturers. Full manufacturing information was turned over to the Navy which in turn issued a contract for the procurement of several thousand tuhes.

### *Ratings*

The ratings of the four different models of spark gap tuhes developed hy the Laboratories are summarized in Table 1. In order to permit the use of these gaps under a wide variety of operating conditions, yet prevent the simultaneous application of the maximum values of peak current, pulse duration, and repetition rate, a special system of rating was evolved. In addition to placing a maximum value on each of these three quantities a maximum value was also placed on the product of any two of these quan-

tities. For instance, one of tbese products would prevent the use of very higb peak currents along with very long pulses, a combination which would give a very short life, especially with aluminum cathode gaps. Or another product would prevent the use of the tube at hoth high peak currents and high repetition rates, a condition which would not allow adequate deionization hetween pulses. The later types of gaps were rated in this manner.

### (g) *Evaluation of the Fixed Gap as a Modulator Switch*

In order to compare the performance of fixed gaps in radar modulators with that of other switching devices, as well as to assess their future possibilities, we may consider them with respect to the following points.

TABLE I
RATINGS OF W. E. FIXED SPARK GAP TUBES

| Tube Type | Repetition Rate—pps | | Peak Current a Max. | Pulse Duration µs Max. | Micro-Coulombs per Pulse Max. | Operating Voltage Range—2 gap Ckt. kv | | Operating Voltage Range—3 gap Ckt. kv | | Peak Trigger Voltage 3 gap Ckt. kv Nominal | Peak Trigger Voltage 3 gap Ckt. kv Nominal | Voltage Required for Starting kV | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min. | Max. | | | | Min. | Max. | Min. | Max. | | | 2 gap Ckt. Min. | 3 gap Ckt. Min. |
| 1B29 | 500 | 2100 | 30 | 0.75 | — | 2.6 | 3.0 | — | — | 3.0 | — | 1.9 | — |
| 1B22 | 300 | 1100 | 75 | 0.75 | — | 3.8 | 5.4 | — | — | 5.0 | — | 2.5 | — |
| 1B31 | 200 | 1600 | 300 | 5.0 | 375 | 7.3 | 9.2 | — | — | 8.0 | — | 6.1 | — |
| 1B42 | 160 | 1500 | 300 | 6.1 | 1280 | 9.0 | 11.4 | 10.5 | 17.1 | 10.0 | 15.0 | 6.5 | 8.5 |

(More complete information on the above tubes is contained in the JAN Specifications for individual tubes.)

1) *Peak current*—The present coded tubes cover a range of currents from 20 amperes to 300 amperes. Experimental tubes have been tested up to 1000 amperes, and indications are that even larger currents are possible.
2) *Switch voltage*—The present tubes cover a range from 2.6 to 17.1 kilovolts. Experimental tubes have heen tested up to 30 kilovolts.
3) *Peak power output*—With the limits of peak currents and voltages on the present tubes, power outputs of 25 kilowatts to 2.2 megawatts are possible. Experimental tubes were made which were capable of furnishing 15 megawatts. Much larger power outputs seem possible.
4) *Pulse duration*—The maximum range of pulse durations covered by any of the present tubes is from 0.25 to 6 microseconds. For pulses shorter than 0.25 microseconds the efficiency of these tubes would decrease rapidly. Pulse durations much greater than 6 microseconds, however, could probably he used if proper attention is given to cooling.

5) *Pulse repetition rate*—A range of 160 to 2100 pulses per second has been covered by coded tubes. Experimental tubes with very short gaps have been tested up to 10,000 pulses per second. However, the design of tubes for practical operation in this region would entail considerable effort.
6) *Operating voltage range*—Although a given set of tubes may exhibit a wide range of operating voltage on a laboratory test, the rated range must be considerably less because of manufacturing variations and changes during life. However, since most radar modulators operate at a fixed power level, this limitation is not a serious one.
7) *Trigger requirements*—The spark gap tubes require a high-voltage low-current trigger supply. While this is more difficult to obtain than the low-voltage supplies required by some other modulators, it caused no real difficulty in practice.
8) *Time jitter*—Although tbe time jitter of coded tubes is of the order of one microsecond, experimental tubes have been made which have, at the operating voltage, a jitter of the order of one hundredth of a microsecond.
9) *Efficiency*—The switching efficiency for all of the past applications of fixed gaps has been in the range of 90 to 96 percent, which makes the fixed gap one of the most efficient switching devices for radar.
10) *Simplicity of manufacture*—Since the unit type of fixed gap has only two elements of simple geometry, its manufacture is relatively easy.
11) *Dependability*—The dependability of the fixed gap has been demonstrated by its satisfactory performance in its extensive application.

## Acknowledgments

The authors wish to acknowledge the valuable help given by many who cooperated in this project. In particular, they would like to thank Dr. S. B. Ingram for his criticisms and suggestions in regard to the development of coded sealed gaps. Also, we are especially indebted to Messrs. H. W. Weinhart and C. Depew for tbeir invaluable help in the design and construction of the large variety of gaps required for this development.